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Panel Discussion
Models and Methods: Can Theory Meet the B Physics Challenge?[1]

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Abstract. The b physics experiments of the next generation, BTeV and LHCb, will perform measurements with an unprecedented accuracy. Theory predictions must control hadronic uncertainties with the same precision to extract the desired short-distance information successfully. I argue that this is indeed possible, discuss those theoretical methods in which hadronic uncertainties are under control and list hadronically clean observables.

The target of B physics is short-distance physics associated with the electroweak and even higher scales: CP violation, CKM elements and the search for new physics. Ideally one wants to gain enough experimental information to disentangle Standard Model (SM) and new physics and to quantify the magnitudes and phases of the CKM elements and the parameters of the new theory precisely. Short-distance physics couples to quarks, but in experiments we encounter hadrons. The theorist's task is to relate the hadronic amplitudes to the quark-level transition and this step involves non-perturbative QCD. It is therefore natural to ask whether theory can keep up with the increasing precision of future B physics experiments like BTeV and LHCb.

It is clear that hadronic models are not an acceptable tool for the extraction of fundamental parameters, because the uncertainties of model calculations are uncontrollable. Unfortunately models are still used to estimate hadronic matrix elements, often in the disguise of 'plausible dynamical assumptions' or similar paraphrases. Yet the only reliable methods to deal with non-perturbative QCD are those which

i) are based on (approximate) symmetries of the QCD Lagrangian or
ii) involve a systematic expansion in a small parameter.

In these cases one can assess the uncertainty of the calculation from the size of the symmetry breaking parameter or the expansion parameter. In certain cases even corrections to the symmetry limit can be computed to first order in the symmetry breaking parameter (often the first-order corrections are simply zero) or sub-leading terms of the expansion can be computed as well.

In b physics the CP symmetry of the strong interaction turns out to be most useful. From the searches for electric dipole moments we know that QCD obeys CP to an accuracy of at least one part in a billion. This allows us to relate the matrix elements of B and $\overline{B}$ decays to each other. In certain cases we can define quantities from which the hadronic physics drops out and the measurement is directly related to the desired short-distance physics. The most prominent example is the CP asymmetry $a_{CP}(B \to J/\psi K_S) = \sin(2\beta)$ [1]. This cancellation of hadronic elements from CP asymmetries usually fails when different operators with different weak phases interfere. We find this situation in K^0–$\overline{K}^0$–mixing or in the 'penguin pollution' in $B \to \pi^+\pi^-$. Actually, there also is a penguin pollution in $a_{CP}(B \to J/\psi K_S)$, but it is suppressed by two powers of the Wolfenstein parameter $\lambda = 0.22$ and a loop factor and yields only a correction of 1% or less. Our second sharpest tool is the isospin symmetry of QCD (relating u and d quarks), which is excellently fulfilled in B decays and e.g. used in the determination of α from $B \to \pi\pi$ decays [2]. Isospin symmetry can be enlarged to $SU(3)_F$, which, however, is broken substantially, because the strange quark mass is much larger then the up and down quarks masses. Especially the U-spin subgroup of $SU(3)_F$, which transforms d and s quarks into each other, is widely used. The $SU(3)_F$-breaking corrections are not always easy to estimate, but usually believed to be below 30%.

The large b quark mass opens the possibility to expand matrix elements in $\Lambda_{QCD}/m_b \sim 0.1$. To this end different observables require different theoretical methods. For inclusive decay rates one can employ an operator product expansion, the *heavy quark expansion* (HQE)

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TABLE 1. Purity classification of theoretical methods. QCDF/SCET is not rated yet.

Rating:	method:	example:
$*****$	CP or isospin symmetry of QCD	$\gamma-2\beta_s$ from $B_s \to D_s^{\pm} K^{\mp}$
$****$	CP or isospin symmetry of QCD plus $O(\lambda^2)$-suppressed penguin	β from $B \to J/\psi K_S$
$***$	HQE	$\|V_{cb}\|$ from incl. decays
	HQET	$\|V_{cb}\|$ from $B \to D^* \ell \nu_\ell$
$**$	four-quark matrix elements from unquenched lattice QCD	$B-\overline{B}$ mixing
$*$	SU(3)$_F$ symmetry	γ from $B_s \to K^+K^-$ and $B_d \to \pi^+\pi^-$

[3]. The HQE is used to determine $|V_{cb}|$ and $|V_{ub}|$ from inclusive semi-leptonic B decays. The leading term in the HQE of these decay rates is given by the calculable b quark decay rate and corrections of order Λ_{QCD}/m_b are absent, so that one can extract $|V_{cb}|$ with a small uncertainty. Heavy Quark Effective Theory (HQET) is another framework employing a systematic expansion in Λ_{QCD}/m_b [4]. It combines features i) and ii), since it exploits extra symmetries occurring in the limit $m_b \to \infty$ to constrain e.g. form factors. A prime application of HQET is the determination of $|V_{cb}|$ from $B \to D^* \ell \nu_\ell$ decays at zero recoil, because here Λ_{QCD}/m_b corrections vanish as well [5]. A more recent development is the application of heavy quark methods to hadronic two-body decays in the framework of *QCD factorization* (QCDF) [6]. A formulation of this concept in the language of effective field theories is the *Soft Collinear Effective Theory* (SCET) [7]. With the help of QCDF/SCET one can express a large class of hadronic decays in terms of a few hadronic parameters and e.g. extract the CKM phase γ from $B \to K\pi$ decays [8]. At present some conceptual issues and the calculability and size of the Λ_{QCD}/m_b corrections are unclear, so that the accuracy of QCDF/SCET calculations is hard to assess. But before the start of BTeV and LHCb we can expect clarifications from the confrontation of the predictions with more precise data. A common feature of all the described heavy quark methods is that possible terms of the form $\exp(-\kappa m_b/\Lambda_{QCD})/m_b^n$ are missed. This issue has been discussed at length for the case of HQE, where it has been speculated that such exponential terms turn into damped oscillating terms proportional to $\sin(\kappa m_b/\Lambda_{QCD})/m_b^n$ [9] ("violation of quark-hadron duality"). While operator product expansions are widely used in many areas of QCD, no such terms have been observed so far. Finally unquenched lattice computations are solely QCD-based, too. Applications to b physics either use effective field theories like HQET or simulations with dynamical b quarks. In the latter case one must take the b mass lighter than in Nature and finally extrapolate to the physical mass using again information from HQET. Also light quark masses cannot be simulated with their actual values and chiral extrapolations are needed. Unquenched calculations are a new topic in lattice QCD and we don't know yet whether all systematic errors are sufficiently under control to take the challenge from BTeV and LHCb. I summarize this discussion with my purity classification in Table 1. There are many more $**$ $***$ and $****$ methods: for example the CP analyses in $B^{\pm} \to K^{\pm} D^0$, $B \to \pi\pi$, $B_s \to \psi\phi, \psi\eta$ and $B_s \to \phi\phi, \phi\eta, \eta\eta$ yielding the CP phases γ, α and β_s, or the determination of $|V_{td}/V_{ub}|$ from $Br(B^0 \to \ell^+\ell^-)/Br(B^+ \to \ell^+\nu_\ell)$.

It should be stressed that also the methods with three or less stars are suited to probe and possibly falsify the Standard Model. b physics provides us with a plethora of observables yielding redundant information on the short-distance physics of interest. New physics couples to quarks, which hadronize in many different ways. The corresponding rates are differently affected by hadronic physics. For example, parity-conserving new physics in $b \to s\bar{s}s$ transitions will possibly be seen first in $B^0 \to \phi K_S$ and then be confirmed through an angular analysis of $B \to \phi K^*$.

One point, however, must be stressed: In the presence of new physics interference effects between the Standard Model (SM) amplitude and the new amplitude introduces hadronic uncertainties. This implies that we can falsify the SM from clean observables, but we cannot necessarily determine the parameters of the new theory cleanly. A prominent example for this situation is $a_{CP}(B^0 \to \phi K_S)$. The best strategy for analyzing hints of new physics is the study of observables which are zero or very small in the Standard Model. Consider the situation that you'll find Δm_{B_s} off from the SM prediction by 10%. Did you find new physics or did the lattice people compute $f_{B_s}^2 B_{B_s}$ incorrectly? If the new contribution to $B_s-\overline{B}_s$ mixing does not come from the CKM mechanism, it will also affect the CP asymmetry $a_{CP}(B_s \to \psi\phi)$, which in this example can be enhanced by a factor of 3 compared to its small SM value. Important "near zero predictions" of the SM are

- certain CP asymmetries,
- certain rare decays,
- FCNC's in the charm system.

As an example I mention the CP asymmetry in flavor-specific decays (meaning $\overline{B} \not\to f$ and $B \not\to \overline{f}$) [10]:

$$a_{\rm fs} = \frac{\Gamma(\overline{B}(t) \to f) - \Gamma(B(t) \to \overline{f})}{\Gamma(\overline{B}(t) \to f) + \Gamma(B(t) \to \overline{f})} = -(5.0 \pm 1.1) \times 10^{-4},$$

with e.g. $f = X\ell^- \overline{\nu}_\ell$. $a_{\rm fs}$ is GIM suppressed in the SM and new physics can give an $O(1)$ contribution.

In conclusion the answer to the question posed to the panelists is definitely yes! There are many four- and five-star observables, which theory can predict with hadronic uncertainties below 1%. Yet once Standard Model contributions and new physics effects are found to interfere, this cleanliness can be lost and one may have to pursue other avenues to quantify the parameters of the new theory precisely. To this end "near zero predictions" of the Standard Model are useful, because they can be dominated by new physics.

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